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A Survey of Spacecraft Charging Events

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A Survey of Spacecraft Charging Events

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This is a survey, or overview, of spacecraft charging events. The emphasis is on concepts and physics, rather than enumerative accounts of projects or detailed statistics of spacecraft.

1. Spacecraft Surface Charging

When an object is placed in a plasma, the object is likely charged negatively relative to the plasma. The reason is because the plasma electrons, being much lighter and faster than the ions, have a larger flux than that of ions. As a result, more electrons impact on the object surface than ions, resulting in a negative surface potential. At equilibrium, the negative potential, repelling electrons and attracting ions, achieves an equality of electron and ion currents.

2. Adverse Effects

Spacecraft surface charging may affect the scientific measurements onboard, such as measurements of the ambient plasma density and energy, the ambient electric fields, and geomagnetic fields. It may also affect contaminations such as ion deposition on the surfaces of spacecraft and mirrors. In extreme situations, it may cause stray signals in telemetry, undesirable signals in circuits, or even erroneous commands in navigation systems.

3. Where does Spacecraft Charging Occur?

Surface charging occurs not only in space but also in the laboratory. The space physicist is mostly concerned with natural charging at geosynchronous altitudes and low Earth orbits (LEO). Deep or bulk charging occurs in the Radiation Belts. Artificial charging can occur during beam emissions from a spacecraft or when the spacecraft has a long tether.

At or near the geosynchronous altitudes, spacecraft charging is important not only because the ambient plasma density is low and energy sometimes high but also there are many spacecraft in that region. At these altitudes, the ion flux is often two orders of magnitude less than that of electrons. Charging up to several kV can occur. The spacecraft SCATHA was launched in 1979 for dedicated study of spacecraft charging at these altitudes.

There is a local time effect at the geosynchronous altitudes. Due to the existence of cross-tail electric fields, the plasma coming from the magnetic tail towards the Earth would drift towards the midnight to dawn sector. Since energetic plasmas often come the tail, the midnight to dawn sector is where charging likely occurs.

At LEO altitudes, charging is at low level, Volts, only. This is because the ambient plasma in this region is dense and not energetic. If the surface potential tries to increase, the opposite charges would be attracted in abundance to prevent any high potential formation.

Since the ions in LEO are slower than a spacecraft, there is a void of ions in the spacecraft wake, where the potential tends to be negative.

The only significant natural charging region in the LEO environment is the auroral zone where the electrons are often directional and energetic.

4. Current Balance

The surface potential at equilibrium is determined by the balance of currents, according to

Kirchhoff's circuital law. Besides ambient plasma electron and ion currents, photoelectron emission plays an important role for high altitude charging in sunlight. Artificial beam emissions of electrons, ions, or both can greatly control the surface potential if the beam currents exceed the ambient currents.

Secondary and backscattered electron emission coefficients are properties of surface materials and are functions of the primary electron energy. For a given surface, if the sum of these coefficients exceeds unity, positive charging occurs. This likely occurs for many materials when the primary electron energies are in the range of about 40 to 1000 eV. The surface condition and the angle of electron impact can also affect the emissions. The coefficients play crucial roles in charging.

5. Onset of Spacecraft Charging

When the ambient plasma is quiet, it can be described approximately by a Maxwellian distribution f(E).

$$f(E) = n(m/2kT)^{1/2}\exp(-E/kT)$$

The current balance equation is given by

$$\int dE\,E\,[\delta(E) + \eta(E)]\,f(E) = \int dE\,f(E)$$

where δ and η are the secondary and backscatterered electron emission coefficients respectively. For Maxwellian distributions, the solution of this equation gives a critical temperature T_* [Lai, et al., 1982, 1983; Laframboise, 1982].

TABLE 1. Critical Temperatures (eV)

Material	Isotropic	Normal
Kapton	800	500
Teflon	2100	1400
Cu-Be	2100	1300
Cu-Be (Activated)	5300	3700
Silver	2700	1200
Gold	4900	2900
MgO	3600	2500
SiO_2	2600	1700

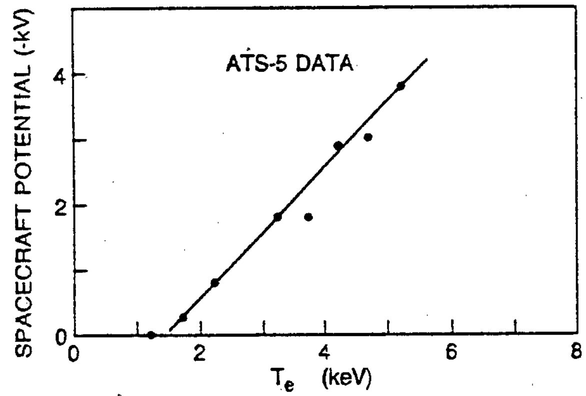


Figure 1. ATS-5 Spacecraft charging data [Rubin et al., 1980]. The existence of a critical temperature manifests.

When the ambient plasma temperature T is below T_*, no charging occurs. As T reaches and exceeds T_*, onset of charging occurs. The charging events on ATS-5 agree with the theoretical predictions [Lai, 1991a].

6. Charging in a Double Maxwellian Plasma

At geosynchronous altitudes, there are occasionally energetic (multi-keV) plasma clouds arriving from the Sun or the geomagnetic tail. When they arrive, the local plasma distribution becomes a double Maxwellian approximately:

$$f(E) = n_1(m/kT_1)^{1/2}\exp(-E/kT_1) +$$

$$+ n_2(m/kT_2)^{1/2}\exp(-E/kT_2)$$

The first one is often of low energy (up to 1 keV approximately) while the second one many keVs. Since secondary and backscattered emissions are important in the energy range up to about 1 keV for primary electrons, the first Maxwellian distribution often favors positive charging. At higher primary electron energies, the emission fluxes are small. Thus, the second Maxwellian distribution favors negative charging. Whether spacecraft charging occurs depends on the competition between the two Maxwellians. On Day 114 of SCATHA, as the first Maxwellian diminishes steadily, the second one wins

eventually, with onset of charging. This event happens to be a triple-root jump in spacecraft potential [Lai, 1991a, 1991b].

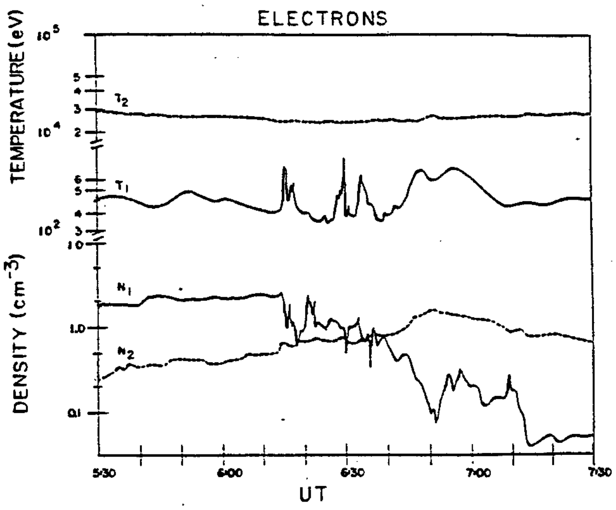


Fig.2 Double Maxwellian parameters on Day 114. [Lai, 1991a]

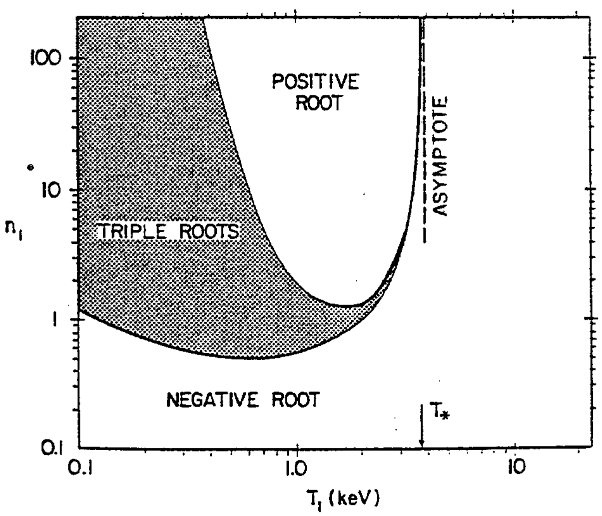


Fig.3 Triple-root domain on Day 114. [Lai, 1991a]

7. Differential Charging

Since different surface materials have different properties such as secondary and backscattered emissions, a spacecraft covered with different pieces of surface materials may suffer from differential charging. It may occur naturally or during beam emissions. When electron beams are emitted, electrons are drawn from the spacecraft ground connected to the beam device. As a result, the dielectric surfaces and the ground become differentially charged.

Differential charging is undesirable because it tends to induce interactions between surfaces of different potentials. Electrons may flow from one surface to another, disturbing scientific measurements onboard or causing anomalies to electronic circuits. In extreme cases, sudden developments of differential charging may lead to sudden discharges, generating harmful electromagnetic pulses.

The amount of charge Q stored between the surface of a thin dielectric layer and the underlying spacecraft ground, for example, is given by:

$$Q = (\epsilon A/d)\,\Delta\phi$$

where d is the thickness, A surface area, $\Delta\phi$ the potential difference. The amount Q may be large for a thin layer, such as a coat of paint.

8. Damage to Onboard Electronics

A most dramatic event occurred on SCATHA. It was the damage of the instruments S2-1 and S2-2 during the emission of a 13 mA, 1.5 keV, electron beam. The spacecraft was charged to near beam energy. The instruments were oppositely deployed booms of about 3m long for measuring the sheath potential. The S2-1 was destroyed when one-third of its boom was in shadow and two-thirds in sunlight. Half rotation period later, S2-2 rotated into the same shadow and was destroyed similarly. This event has been fully documented [Cohen et al., 1981] but the exact cause was never found.

9. Anomalies due to Surface Charging

Anomalies occur occasionally during surface charging. For a recent example, a lockup of a microprocessor unit on a DMSP satellite [Anderson and Koons, 1996] occurred during a surface charging event of about 500 V in the auroral zone. The layered structure of the thermal dielectric blankets on that spacecraft had a large capacitance, and, a discharge in the thermal blankets probably caused

the anomaly [Anderson and Koons, 1996].

Vampola [1987] has presented a survey discussion on many anomaly events, especially those due to deep dielectric charging.

10. Deep Dielectric Charging

The Sun controls the Earth's space weather. Occasionally the Sun emits an energetic plasma cloud called a solar coronal mass ejection. The plasma in the cloud often reach MeV and beyond. Since energetic electrons and ions can penetrate deep into materials, they deposit inside. The depth of deposition depends on the energy of the incoming electron or ion. At MeV energy, electrons penetrate deeper than ions. A MeV plasma impacting on a spacecraft surface material would form a double layer, the deeper layer being that of electrons. For dielectrics, the deposited charges can stay for hours and even days. They migrate and escape slowly because of the low conductivity of dielectrics, and may cause little harm if the flux is low or the neutralization process is slow.

11. Effects of Deep Dielectric Charging

Deep dielectric charging gives typically very low spacecraft surface potential. This is mainly because the energetic (MeV) fluxes are small. Furthermore, the electrons, although more abundant, are deposited deeper than the ions, which are deposited nearer the surface.

Violet and Frederickson [1993] reported that many anomaly events occurred on CRRES during low spacecraft surface potentials. They occurred when CRRES was in the Radiation Belts where deep dielectric charging can take place.

Although the MeV fluxes are usually low, the density of charges deposited can accumulate over time. Local electric fields can reach up to 10^6 to 10^8 V/m [Hastings and Garrett, 1986] which may cause breakdowns.

Despite their low fluxes, some MeV electrons may penetrate into the electronics onboard. It is known that there is significant correlation between high fluences of electron depositions and anomalies in some types of electronic devices.

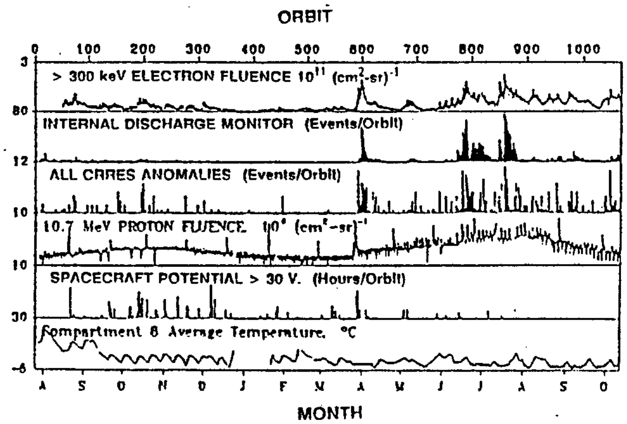


Fig.4 Deep dielectric charging on CRRES. [Violet and Frederickson, 1992].

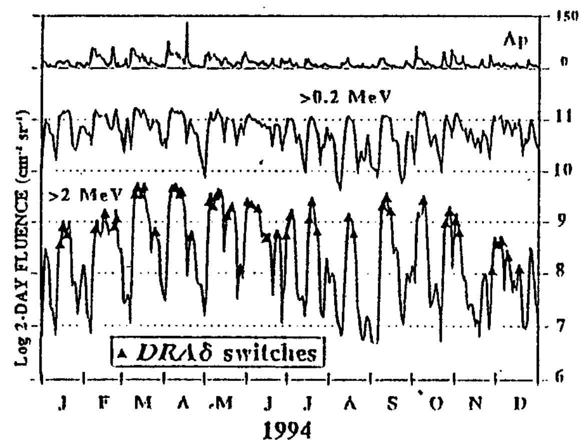


Fig.5 Deep dielectric charging on DRAδ. [Wrenn, 1995]

At energies of about 100 MeVs or higher, ions can penetrate into materials deeper than electrons and produce cascades of ionization. Such energetic particle fluxes are very small.

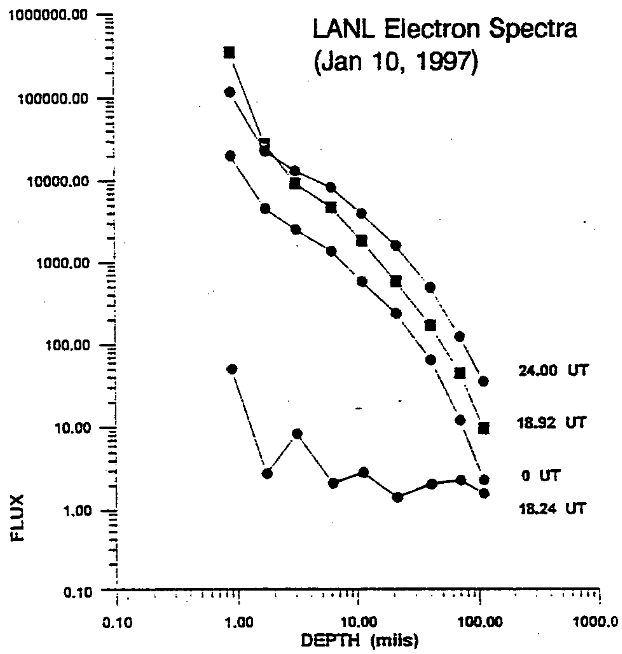
For more on spacecraft anomalies due to the radiation environment, see, for example, Lauriente et al. [1998].

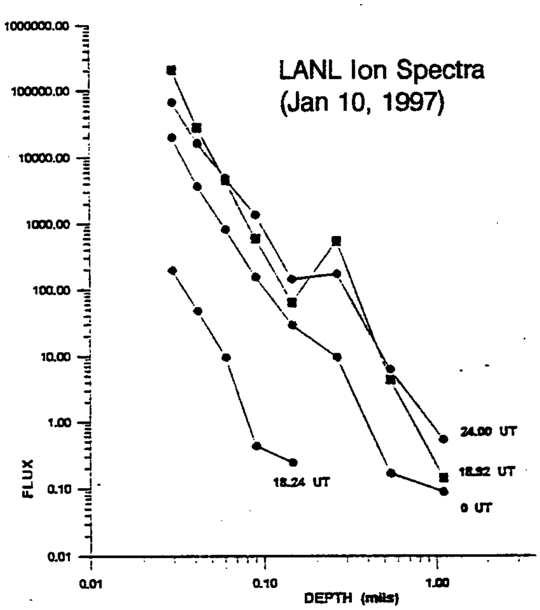
12. AT&T Telstar 401

On Jan 11, 1997, AT&T Telstar 401 at geosynchronous altitudes failed (EOS, 49-51, 1997; www-istp.gsfc.nasa.gov/istp/cloud_jan97/att.html and umbra.nascom.nasa.gov/istp/ SHINE_report.html). A solar coronal mass ejection cloud of energetic plasma (MeV) arrived at the geosynchronous region

a day earlier and the cloud passage lasted a day. The Telstar failure occurred after the passage of the cloud. While the exact mechanisms of the failure are still at large, a common view seems to be deep dielectric charging.

The following figures show the electron and ion spectra in a geosynchronous vicinity of Telstar 401 on Jan 10, 1977. The depths of deposition are calculated by using the typical energy-deposition relation in Hastings and Garrett [1996].





13. Discussions

The exact mechanism of the failure may never be found. A few comments are as follows:

(1) The spatial distribution of electron and ion depositions is time dependent. Since the electron flux is orders of magnitude higher than that of ions, the electron layer is formed first. After a cloud passage, the ambient plasma is not energetic but more dense. The ion layer is then formed near the surface. Thus, a discharge is more likely after a storm passage.

(2) Electrons stay inside dielectrics for days. It takes time for them to migrate. However, what triggers them to avalanche during the migration is still unknown.

A case in point is Vampola's [1987] citation of Robbins [1979], who reported that anomalies on Meteosat occurred days after the passage of storms, not during them.

Wrenn [1995; 1996] show good correlation between high fluences and anomalies on DRAδ. However, the figures are not plotted in fine time scales.

The Telstar 401 event reminds us of the failure of another geosynchronous satellite, ANIK E1, which occurred after two weeks of energetic conditions [Baker, et al., 1997].

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